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Learning in dedicated wood production systems: Past trends, future outlook and implications for bioenergy

Marc de Wit [1], Martin Junginger*, André Faaij

Energy & Resources, Copernicus Institute of Sustainable Development, Utrecht University, Budapestlaan 6, NL-3584 CD, Utrecht, The Netherlands

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A B S T R A C T

This paper assesses the learning potential of dedicated wood production systems to boost yields and reduce production costs. In particular, the paper analyses past trends and provides a future outlook of developments in dedicated wood production for three cases: eucalyptus production in Brazil, poplar production in Italy and willow production in Sweden. A main objective of this paper is to evaluate the extent to which experience curves can be devised for conventional woody plantation systems, and whether these can also be applied to short rotation cropping (SRC) production systems. For current average SRC production systems, Italian poplar shows the highest cost at 5.5 € GJ^{-1} followed by Swedish willow at 4.4 € GJ^{-1} and Brazilian eucalyptus is produced to the lowest costs at 2.8 € GJ^{-1}. It was assessed to what extent production costs can be reduced per step in the production cycle and how this affects the minimum cost levels that can ultimately be achieved. Ultimate cost reduction could lead to delivered costs of 2.2 € GJ^{-1} for poplar, 1.9 € GJ^{-1} for willow and 1.9 € GJ^{-1} for eucalyptus on better quality lands. Based on historic cost data and production trends, experience curves were applied providing progress ratios for poplar in Italy and eucalyptus in Brazil. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The extent to, and rate at, which cost reductions can occur within the next 20 years were evaluated by combining current costs, minimum cost levels and progress ratios with ranges in European and global biomass demand projections. This shows that, at the assumed growth rates for biomass production in Europe and for global production, minimum cost levels can be reached within the next two decades for all cases.

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* Corresponding author. Tel.: +31 30 2537 613; fax: +31 30 253 7601.
E-mail address: H.M.Junginger@uu.nl (M. Junginger).
[1] Dr. Marc de Wit is currently employed at Kirkman Company as a consultant in the New Energy and Resources practice.

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1. Introduction

The production and use of wood resources expands globally, increasingly for energy applications. Main drivers for its use as a source of energy are diversification and the mitigation of energy related greenhouse gas (GHG) emissions through substitution of fossil fuels. At present, important applications for solid bioenergy include domestic and district heating and co-firing in power plants [1]. Potential future uses include (advanced) biofuels production and biobased chemicals and materials [2]. These fuels and chemicals will to a large extent be produced from lignocellulosic biomass from forests and dedicated plantations.

Global productive forest plantations amounted to 109 million hectares by 2005, increasing at a rate of 2.0 million hectares per year during the 1990–2000 period and at 2.5 million hectares per year from 2000 to 2005 [3]. Market conditions in the global wood industry are changing: for example forest plantations supply an increasing share of total forest products and an increasing competition for wood fibres between the energy industry and the traditional forest industry is observed [4]. One particular development has been a global increase in short rotation cropping systems for energy use. These systems rely on high density planting, rapid growth and short harvesting cycles (typically 1–7 years). SRC may refer to herbaceous crops such as miscanthus and switch grass and woody species like pine, poplar, willow and eucalyptus [5].

Short rotation crops (SRC) are species and cropping systems selected and optimized for their fast growing and high yielding characteristics. These crops are produced around the globe for example willow is produced in the Sweden, the UK, the US and Poland; eucalyptus is produced in Brazil, India, China and India and poplar is produced in China, India and Italy.

The continued deployment potential for woody biomass sources critically depends on how technological learning proceeds and subsequent cost reductions are established as these can improve the economic competitiveness and thus market share of bioenergy systems compared to fossil and other renewable options [6]. Analyses that relate technological learning and cost reductions to the degree to which a technology is utilized can be quantified using experience curves. A comprehensive overview of existing literature on experience curves for fossil and renewable technologies is provided by Junginger et al. [7], including bioenergy applications [6,8,9]. De Wit et al. [6] illustrated the strong influence of learning rates of different biofuel production routes (in Europe) for their respective deployment. Data on perennial cropping in that analyses were based on crude assumptions only. Three recent studies have analyzed cost reductions in cropping systems for US corn [10], Brazilian sugarcane [11] and German rapeseed [12]. These studies found progress ratios, the rate at which production costs can be reduced with every cumulative doubling of established production, of 55, 68 and 80%, respectively.

Similar assessments for dedicated perennial wood cropping systems are lacking. Challenges exist with regard to data quality, consistency and level of detail. Because dedicated wood production for energy is still limited, data are scarce and more fragmented than for the annual crop cases mentioned. To deal with this, analyses could rely on data from the production of wood for conventional applications such as for timber and fibre, for which established industries exist that have been producing for many decades. Limitations exist, however, due to the different requirements for differing applications such as to straightness, thickness, density and cellulose content. These different demands influence the cultivation system with respect to coppicing, rotation periods, fertilization requirements, harvesting and hence influence production costs.

A main objective of this paper is to evaluate the extent to which experience curves can be devised for conventional woody plantation systems, and whether these can also be applied to SRC production systems. Typically, a key methodological challenge in experience curve analysis is related to the choice of system boundary (with regard to time frame and geographic scope). The impact of these choices on the results will be investigated in detail. Furthermore, the present paper aims to provide an overview of past developments, the current status and an outlook of costs and yield developments in dedicated wood production systems for energy. It provides a review of quantitative data and identifies the driving forces that have shaped past developments. To evaluate the future cost reduction potential for dedicated wood cropping systems, both bottom-up insights and top-down approaches (including experience curves) are combined and applied to global and European demand projections to sketch scenarios for future deployment of SRC systems and possible developments in production costs.

Section 2 describes the methodologies that are used, the methodological challenges encountered and specifies the data gathering efforts. Section 3, gives an overview of SRC cropping systems and specifies the specific systems assessed in the present study and present bottom-up cost breakdowns. Section 4 starts with an overview of past developments in wood production systems, applies experience curves to them and derives progress ratios. Next, cost reduction options and the preconditions to achieve those are applied to current average cost levels and

derive minimum cost level that can ultimately be achieved. The progress ratios are applied to European and global demand projections to analyze how fast and when minimum cost levels can be reached. Finally, in Section 5, the outcomes are discussed and conclusions are drawn.

2. Methodology

To assess future developments in SRC wood production systems, a main aim of the present paper was to construct experience curves based on past production costs and produced volumes. This approach was found to be difficult as a result of data limitations. In order to explore the opportunities for performance improvements and sensitivities in SRC production systems the present study contains three methodological steps. Firstly, an overview is given for current average bottom-up production costs and yield levels and, based on bottom-up data-review, minimum cost levels are derived. Secondly, historic developments in the performance of these systems are assessed in order to specify developments in production cost levels and yields and to derive first order estimates for progress ratios of those systems. Thirdly, Future prospects for cost reduction are explored by assessing the rate at which cost can decrease by linking the derived progress ratios to global and European demand projections. Verification with bottom-up derived minimum cost levels allows to explore if and when these levels are reached.

2.1. Data gathering and challenges

Data availability for SRC wood production systems is more constrained and fragmented compared to annual cropping systems, for several reasons: fewer statistics are recorded by (inter)national statistics bodies; data are often not (made) publicly accessible; companies operate the entire value-chain and rely on bilateral trade contracts instead of trading on the market (no commodity market), etc. For all cases, it was found that knowledge institutes that collaborate with and are involved in R&D developments for the industry provide the richest source of information. Primary data were collected through field research at knowledge institutes in Brazil (State University of Campinas, Brazil), Italy (Consiglio per la ricerca e la sperimentazione in agricultura (CRA), Casale Monferrato, Italy), Sweden (University of Agricultural Sciences, Uppsala, Sweden) and Poland (Institute for Fuels and Renewable Energy, ECBREC, Warsaw, Poland). Field research involved conducting expert interviews and collection of data from (the archives at) these institutes and national statistics of these countries.

2.2. Bottom-up cost analysis and minimum cost levels

Bottom-up cost data are presented for the typical current cultivation and management practices. Cost breakdowns distinguish between establishment, maintenance, harvest and local transport. Costs are discounted and presented for normalized annual per hectare costs per step of the production cycle, including ranges in these costs). These cost levels are linked to average current yield levels to derive per gigajoule production costs. Possibilities and options for improvements in cultivation and cost reductions (summarized in Table 3) are obtained from expert interviews and literature review and quantified whenever possible. Based on this inventory the total improvement potential and ultimately minimum cost levels are quantified.

2.3. Top-down cost analysis: Experience curves

An experience curve approach can be applied to analyze historic cost developments, assuming that the performance of a cropping system (i.e., production costs) changes by a fixed fraction with every doubling of established production or exercised activity (cumulative volumes of wood produced) [13]. Comprehensive literature exists on the principles, applications and verification of this method [14]. The experience curve can be expressed as a power law:

$$C_t = C_o (P_t / P_o)^b \tag{1}$$

where C_t is the unit production cost at a future time t; C_o is the initial unit cost at the start of (commercial) production $t=0$; P_o is the cumulative production at an initial start of (commercial) production; P_t the cumulative production at a future moment. A progress ratio (PR) can be derived that expresses the costs after one doubling in cumulative production. The PR can be derived from the learning rate b: $\mathrm{PR}=2^b$. The uncertainty of the curve fit is reflected by the progress ratio error (σ_{PR}); as described by van Sark [15] after Bevington [16].

Four key examples that have successfully applied an experience curve to historic cost developments of annual crops used for biofuels are highlighted:

- Brazilian sugarcane production for ethanol has achieved a 60% cost reduction between 1975 and 2004, resulting in a progress ratio of 68% [11].
- Similarly, US corn production saw a cost reduction of 63% in 30 years, resulting in a PR of 55% [10].
- Rapeseed production in Germany for diesel shows similar figures with production costs declining 70% between 1971 and 2006, the equivalent of a PR of 80% is found [12].
- For wood fuel supply chains from primary forest residues in Sweden a PR of 87% was found [17].

The analysis of annual cropping systems in these studies relies on extensive and consistent data sets that for several decades have been recorded by (inter)national statistics bodies (e.g., Eurostat, Faostat, USDA [18]) to keep track of the status and progress of the agricultural sector.

A main methodological challenge in experience curve analysis is related to the applied system boundary, both in time and geographic scope, for which calculated progress ratios are particularly sensitive. Determining the first (unit of) production is complex because the early phases of production are often poorly recorded. In the case of Brazil, the period that lies between the start of eucalyptus production and large-scale commercial production covers more than a century. For poplar production no statistics were available from the early years of production. Learning systems are often not restricted to national settings. Therefore, to assess sensitivities, progress ratios were derived both by applying cost reductions to national and to global production volumes, at least for the case of eucalyptus. A mechanism that stimulates performance improvements is knowledge and technology spill-over between similar crops produced in different countries or between different crops produced in the same country. In many cases, technologies in their initial development are only produced in a single country, and it thus suffices to account for the national cumulative production. However, as soon as the same technology is also produced or implemented in other countries, ideally the joint (global) cumulative production should be used when devising experience curves. Taking again the example of eucalyptus production Brazil, this is difficult to determine, as eucalyptus has also been produced in many other world regions, yet specific experiences (e.g., the use of eucalyptus for the production of charcoal for steel making) is limited to Brazil. To address the sensitivities of choice of geographical scope, different biomass demand projections for national or global developments are used when evaluating how rapidly minimum cost levels can be reached.

2.4. Exploring minimum cost levels and development rates: Top-down versus bottom-up

To explore the extent to, and pace at, which production costs can go down, the bottom-up and top-down outcomes are combined. The application of progress ratios to demand projections can give an indication at what speed future costs can decline. However, simple extrapolation can result in impossibly low projections for cost levels. Bottom-up cost analysis, on the other hand, can provide insight into the improvement potential of every step of the production cycle and derive minimum cost levels, but can in itself give very limited information on the potential speed of development. A combination of these approaches is recommended for realistic projections for future cost developments (see [19]). Related to this issue is the notion that experience curves assert that the PR is fixed for a production system through different stages of technological maturity [14]. Empirical findings suggest [20,21] that at some point of technological maturity (for example when the turning point in the S-shaped market diffusion curve [22] is reached) the experience curve flattens and PRs will increase. These dynamics emphasize the importance of understanding the fundamental driving forces and limitations for cost reductions, which is why these aspects are combined in the analysis [23].

3. Production settings, costs and historic developments

3.1. Cropping systems

Table 1 presents an overview, for the three cases, of the climatic conditions, the cropping system configurations and applications for which wood is produced. Short rotation crops (SRC) are species and cropping systems selected and optimized for their fast growing and high yielding characteristics. SRC can either be grown as single-stem crops or as a multiple-stem crop in which case, after a first harvest, the crop's coppices (willow) are harvested. When optimized for achieving maximum yields, and depending on being a single or multiple-stem crop, SRC are typically harvested after 1–7 years of planting [5].

Three types of eucalyptus plantations are considered for Brazil: (large-scale monoculture) plantations either produced as (1) single stems or (2) coppiced in SRC production systems and (3) agro-forestry systems. Coppiced production was initiated for the production of bioenergy feedstocks operating higher plant densities. Agro-forestry systems produce eucalyptus at modest plant densities combined with food crops (mainly rice, soy and maize) and livestock grazing when trees get bigger. Agro-forestry plantations are often practiced by out-growers; farmers that are contracted by industries to produce eucalyptus. Willow production is only considered for SRC production, optimized for calorific output, produced in coppiced form at high plant densities. To stimulate sprout formation willow is cut back, depending on the species, in the first, second or third year after planting [24]. Poplar production is either produced for traditional applications such as for construction and paper and pulp or as an SRC crop for energy.

3.2. Sector developments

Figs. 1 and 2 presents the produced wood quantities over time for poplar in Italy [25], willow in Sweden [26] and eucalyptus in Brazil [27]. Number symbols in the graphs indicate events and developments that led to changes in production volumes, these are further discussed below. In addition, these figures are used to derive cumulative production quantities that are use in Section 4.1 to fit experience curves.

3.2.1. Brazilian eucalyptus

Sizeable eucalyptus production in Brazil started in the beginning of the 20th century. Developments were gradual until the late 1960s after which it accelerated to peak at almost 4 million hectares in the mid 1980s. It then dipped at 3 million hectares around 2000 and has since then been growing and breached 4 million hectares in 2007 [28]. While the introduction of eucalyptus production in Brazil was in 1824 (1) the first industrial plantations were established in the 1900s [29] to provide fire wood, telegraph poles, sleepers for railway companies and lumber for new towns along the railroad [29]. (2) The production of high grade bleached pulp for paper making started in the 1940s. Next to plantations in São Paulo state, plantations expanded to the state of Minas Gerais for charcoal production, supplying to the iron and steel industry [30]. (3) By 1966, nearly half a million hectares of eucalyptus plantations were established, 80% located in the state of São Paulo [31]. In that year, a reforestation program (PIFFR) was launched to secure forest supplies for the decades ahead, mainly for charcoal and paper and pulp production. As a result, production increased to 6 million hectares by 1988 [32]. (3) In addition, in 1974, after the oil crisis the federal REPEMIR program aimed at substituting imported fossil fuels by forest products. The program, providing financial support, mainly boosted expansion in regions where land prices were low in the central-west and south-east. Production in these regions was unsuccessful due to low water availability that restricted yields while its remote location drove-up transport costs. Learning from this experience, the sector professionalized aiming for a better transfer of knowledge, technologies and methods. For example by improving selection criteria for

Table 1
Production characteristics for SRC production: poplar in Italy, eucalyptus in Brazil and willow in Sweden.

	Eucalypt			**Poplar**		**Willow**
	Mono-culture single stem	Agro-forestry	SRC	Traditional	SRC	SRC
Cases Country Climatic zone(s)	Brazil (sub)tropical, temperate in South			Italy Temperate and Mediterranean, Alpine in North		Sweden Temperate, subarctic in North
Production system						
Type	Stem	Stem	Coppice	Stem	Stem/ coppice	Coppice
Plant densities (plants ha^{-1})	~1500	~100	~1100–2 200	~300	~10 000	~12 000
Lifetime of plantation (years)	15–21	15–21	8–12	10–15	10–15	10–21
Rotation length (years)	5–7	5–7	2–3	10–15	1–5	1–3
Biomass applications	Paper and pulp, iron and steel (charcoal), timber	Timber	Energy	Plywood, sawing wood, particle board, paper and pulp	Energy, paper and pulp	Energy (electricity, heat and biofuels)

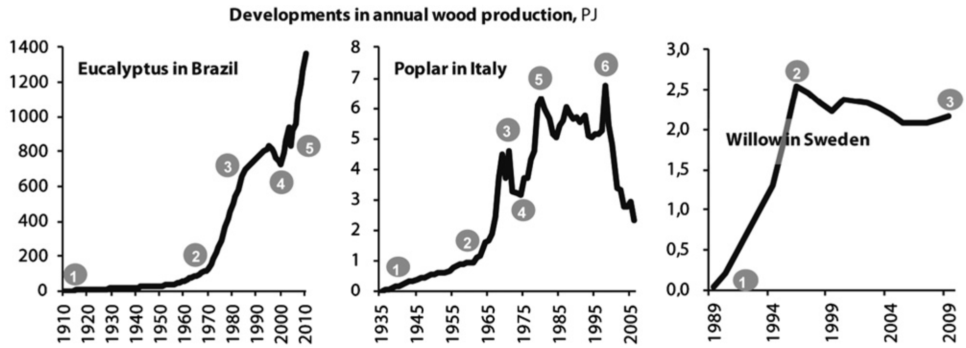

Fig. 1. Developments in the production of poplar in Italy (ISTAT (Istituto nazionale di statistica) [33,69]), willow in Sweden (Helby et al. [36]; Statistiska centralbyrån (SCB), [114]) and eucalyptus in Brazil (Associacao Brasileira de Celulose e Papel (BRACELPA) [53]). Number symbols in the graphs indicate events and developments that led to changes in production volumes, these are further discussed below.

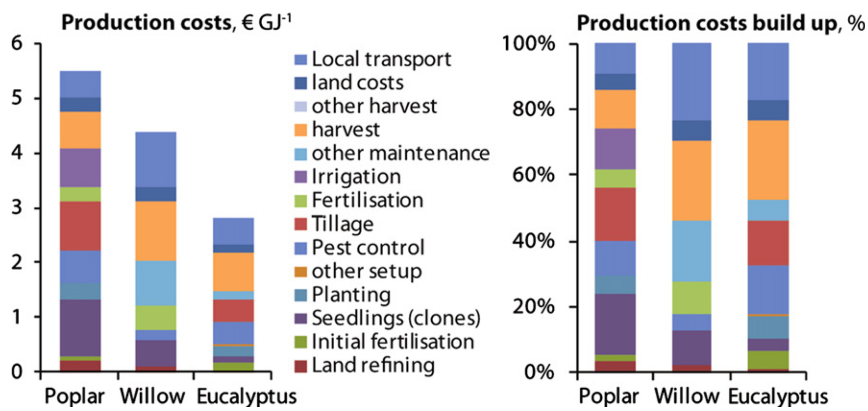

Fig. 2. Breakdown of average current production costs for cultivation of poplar, willow and eucalyptus for harvest, the (opportunity) costs of land and the costs for local transport (left) and the relative contribution of the production steps to the overall costs (right). Based on data presented in Table 2.

the optimal species given site-characteristics, improving the silviculture and genetic improvements to optimise plant characteristics. (4) During the 1980s, forestry companies sought expansion of their production by contracting local farmers (out-grower schemes). While foresters could expand the resource output, farmers generated an additional and fixed income. From the 1990s, increasing concerns about adverse effects of large-scale monoculture forestry such as erosion, nutrient runoff and wildlife habitat loss were addressed with the introduction of certification schemes, like FSC, through the implementation of integrated forest management practices.

3.2.2. *Italian poplar*

Poplar production in Italy [33] developed erratically; starting around 1935, production increased until the late 1970s, stabilizing during the 1980s and gradually declining afterwards until 2006. While traditional plantations are operated since production began, SRC plantations started operation only around 1994 [34]. (1) By the 1930s, demand for wood increased for which the production and supply of poplar became the industry standard. (2) After the war, economic recovery spurred the demand for wood resources for furniture, packaging and particle board for construction until the end of the 1960s. (3) Subsidies in the form of price guarantees for food crops made poplar less profitable and more risky compared to food production which stalled and even reduced poplar production in the 1970s. (4) The oil crises drove up fossil energy and raw material commodity prices, boosting profitability and hence production of poplar for the plywood and chipboard sector. (5) In the 1980s, a reorganization in the plywood industry, triggered by increased competition with particle board for the furniture industry, caused a decline in poplar production. This decline in the number of farmers active in poplar production was accelerated by stricter environmental regulation such as restricted fertilization levels. During the early 1990s, wood prices strongly devaluated because a change in waste legislation from then on allowed discarded (waste) wood to be used in the chipboard industry. Although at the same time the demand for wood pellets for energy use increased, this only stabilized poplar production since most of that particular demand was met with imported conifer wood. The 1990s also saw the first use of poplar production for electricity generation purposes by the large utility ENEL. (6) Since 2000, production has continued to decrease due to a strong volatility in wood prices, putting the profitability of production under pressure. This situation worsened when a financial aid scheme initiated by the Italian government, which successfully increased the area under poplar production, was abolished shortly after because it was found to be incompatible with EU regulations.

3.2.3. *Swedish willow*

Commercial willow (Salix) production in Sweden started in the early 1990s increasing fast, peaking in 1996 at 16 000 hectares, declining afterwards and stabilizing at around 14 000 hectares to the present day. Optimized for calorific output, willow is produced in coppiced form at high plant densities. Though the amount of land under willow produced has increased since the 1980s, production is still small scale. (1) Starting in the 1980s, Salix production in Sweden received attention for its potential use as an energy crop. In 1984, research grants stimulated the

research, development and deployment (RD&D) in Salix breeding, leading to the development of clones with improved characteristics such as higher yields and frost resistance [35,36]. Apart from the potential of energy crops to replace fossil fuels, it offered an attractive alternative to replace conventional agricultural crops.(2) As a result of reforms of EU's common agricultural

Table 2
Discounted annual production costs per hectare per step of the cropping system for current management for eucalyptus, poplar and willow.

Production cycle steps	Costs[a,b] per activity					
	Eucalyptus		Poplar		Willow	
	Value	Range	Value	Range	Value	Range
Yield (t ha^{-1} y^{-1})	18.2[i]	17–20	14	9–18.5	10[n]	6–12[n]
Setup						
Land purchase (€ ha^{-1}) or opportunity costs (€ GJ^{-1})	4000[h] (purchase)	1600–4000[h]	0.25[g] (Opportunity)	0–0.5[g]	0.25[g]	0–0.5[g]
Land refining (€ ha^{-1} y^{-1})	3[i]	–	32[c]	32–39[c]	9.5[s]	3.8–11.9[s]
(Initial) fertilisation (€ ha^{-1} y^{-1})	16[i]	6–25[k]	7[c]	7–14[c]	39[t]	0–85[t]
Seedlings or clones (€ ha^{-1} y^{-1})	12[i]	4–11[k]	168[c]	75–168[c]	See planting	
Planting routine (€ ha^{-1} y^{-1})	20[i]	–	50[c]	45–50[c]	41[p]	38–43[p]
Other setup (€ ha^{-1} y^{-1})	3[i]	–	–		3	–
Maintenance						
Pest control (€ ha^{-1} y^{-1})	45[i]	31–95[l]	93 [d]	76–110[d]	17[r]	10–21[r]
Tillage (€ ha^{-1} y^{-1})	43[i]	–	144 [d]	129–159[d]	–	–
Fertilization [d] (€ ha^{-1} y^{-1})	see setup	–	46 [d]	32–60[d]	See pest control	
Irrigation (€ ha^{-1} y^{-1})	–	–	112 [d]	0–218[d]	–	–
Other maintenance [f] (€ ha^{-1} y^{-1})	18[i]	–	–	–	0.81[q] (GJ)	–
Harvesting (€ ha^{-1} y^{-1})	75[i]	58–98[m]	108 [e]	60–150[e]	95[o]	24–95[o]
Local transport (€ t^{-1} or € GJ^{-1})	0.49 (GJ)[j]	0.28–0.69[j]	0.5 (GJ) [f]	0.15–0.5	17.5 (t)	16.6–18.4

NB—Yields are discounted in the calculation of production costs. The yields presented in the table are not discounted yields.
[g] Yields are based on Bergante and Facciotto [39].

[a] All costs in Euros are reported for the year 2010. Costs and prices are assumed to be the yearly average of the year in which the study was published unless reported otherwise. Cost figures were converted between currencies and over time in two steps. First, values were corrected for inflation or deflation (to December 2009) in the currency in which costs were stated. Second, values were converted to Euros applying the exchange rate for December 2009 [50].

[b] Discounted cash flow analysis was applied to calculate the (net) present value to the first year of the plantation to account for the unequal distribution of costs and revenues over the plantation lifetime. Revenues (benefits) of wood plantations exist mainly of the harvested wood after subsequent rotations. The primary interest in the present study is to derive the discounted production costs rather than net profits which would involve the inclusion of market prices to which harvested wood could be sold at the time of harvest. To account for the monetary value that the physical harvest represents at the moment of harvest, physical streams are also discounted. Ample literature exists on the subject of discounted cash flow analysis for wood plantations, e.g., see [51]. The discount rates used were 10% for Brazil and 7% for Italy and Sweden.

[c] Establishment costs for poplar are based on personal communication by Pablo Lopez with Mr. Gianni Facciotto in 2009 [41]. Costs were specified for typical short rotation forestry (SRF) plantation of 7000 plants per hectare for a 10-year plantation, presented under 'value'. No variations in the costs were specified for the SRF plantation setup costs. Therefore, as an indication for the cost range the costs for traditional plantations, from the same source, are presented under range, sometimes as the lower limit and sometimes as the higher limit. Land refining: sums the cost for ploughing and a step referred to as additional land refining.

[d] Maintenance costs are based on Coaloa and Vietto [40]. Apart from specifying values, cost reduction estimates are given for chemical pest treatment, soil management and fertilization of 31%, 19% and 47%, respectively, without specifying a timeframe over which this could be realized. The typical cost values are considered to represent the high-end of costs. Improvement options the 'value' refers to the average of these two.

[e] Harvest costs: based on Bergante and Facciotto [39].

[f] Transport costs are based on Gasol [46] who reports cost indications for transport per gigajoule.

[g] Rosenqvist et al. [47] suggest to use the opportunity cost of land as a measure of land costs. They estimate the opportunity cost of land for willow production in Sweden at between 0 and 0.5 € GJ^{-1} currently and between 0 and 0.4 for the future. These same values were used for Italy.

[h] The costs of land were taken from a study by Centro de Inteliência em Florestas [43]. While in most states land prices averaged 800–2400 € ha^{-1}, the state of São Paulo experienced prices of up to 4000 € ha^{-1}. The cost of land varies considerably depending on land quality and proximity to facilities and end-use markets. Purchase costs were depreciated over three plantation lifetimes of 21 years to make them comparable to the (opportunity) land rents that were used in the other cases.

[i] The costs of eucalyptus production are mostly based on a study by Centro de Inteliência em Florestas [42] who reports on the costs of eucalyptus production for a typical Brazilian plantation in the state of Minas Gerais operating three 6-year rotations at a plant density of 1600 plants per hectare and generates a gross yield of 820 m^3 over the 18-year plantation lifetime, equivalent to 18.2 t ha^{-1} y^{-1}.

[j] The costs for local transport were based on personal communication at STCP in 2009 [52]. Costs are specified per tonne kilometer (t km) for two transport distances: at increasing distances the costs per t km decline. STCP estimates costs at 0.30 R$ $(t\ km)^{-1}$ below 50 km and 0.12 R$ $(t\ km)^{-1}$ at distances over 150 km. More than half of all transport was under 100 km in 2008 [53].

[k] Centro de Inteliência em Florestas (2008) [54] estimates a variation in the costs for fertilizers, harvesting and transport that depend on the level of mechanization and inputs that are applied. Based on the ultimate range provided by CIF (2008) the extremes are determined relative to average management and input levels this results in a $\pm$61% variation.

[l] Included in the pest control are the costs for weeding. Van den Bos [27] reports the costs for weeding, after [55], distinguishing between chemical and manual and weeding, which varies between 99 and 300 R$ ha^{-1} y^{-1}, respectively.

[m] The low end of harvesting costs, based on personal communication by Arno van den Bos with Mr. Seixas in 2009 [56], is estimated at 10 R$'09 m^3. A high estimate of 17 R$'09 m^3 was based on personal communication at STCP in 2009 [52,57].

[n] Christersson [35] estimates yields of 6–8 t ha^{-1} y^{-1} when extensively managed and 10–12 t ha^{-1} y^{-1} when intensively managed on commercial scale plantations.

[o] Harvesting costs increase with higher yields. Based on expert interviews and supplemented with findings from Lantmannen a range of 350–550 € ha^{-1} per rotation of three years was found. The lower estimate is based on [49,58] who expect that when improved harvesting equipment is commercially produced in series it can be produced to one-fourth of the current costs.

[p] Planting of 12 000 plantings is considered. Costs are not specified for the plantings and the planting operations.

[q] Costs for other maintenance were taken from Rosenqvist et al. [47] who specifies costs (in € GJ^{-1}) for brokerage (0.25), administration (0.15), restoration (0.04) and overhead (0.37).

[r] Total costs were presented for weed control and the application of potassium and phosphorus fertilizers in all but the years when crops are harvested. An average amount of 45 € ha^{-1} y^{-1} was reported and a range of 25–55 € ha^{-1} y^{-1}.

[s] The costs for operations performed before every planting (pre-planting) include ploughing, harrowing and herbicide (glyphosphate) application. Reported costs were 200 € ha^{-1} and a range of 80–250 € ha^{-1}.

[t] Costs were reported for nitrogen fertilization 200 € ha^{-1} per rotation with a range of 0–432 € ha^{-1}. At the lower end no fertilization was considered.

policy (CAP) and a Swedish reform (Omställning 90) in the early 1990s, financial support was cut, e.g., intended to reduce cereal production. To offer an alternative, subsidies were granted in Sweden to farmers who switched from cereal production to other land uses, including Salix. Quite many of the farmers that switched were older farmers that wanted to reduce their working hours on the farm. Boosted by these subsidies, by 1996, 16 000 hectares of Salix were established [37]. The 1990s reform had been the initial step in a process aiming at deregulation of farm support and transforming to a more market oriented agricultural sector. The process slowed when in 1995, Sweden joined the EU and farmers were eligible for CAP support when cross compliance criteria were met. This again stimulated cereal production and leaving land fallow. On top of subsidies for the switch to and establishment and production of Salix as an energy crop, fiscal incentives and subsidies were introduced to stimulate the purchase of biomass fuelled combined heat and power systems (CHPs) or the retrofitting older systems [38] although this apparently did not stimulate further growth of willow production.

3.3. Cost breakdowns

Table 2 shows the production costs for the three cases for average current SRC cultivation and the ranges in these values. The ranges identified in the values stem from deviations from average cultivation practices, e.g., due to site-specific circumstances and from opportunities to improve. These latter improvement options are summarized in Tables 3–5. summarizes the cost breakdown of the current average production systems. Italian poplar shows the highest cost followed by Swedish willow; Brazilian eucalypts is produced to the lowest costs. For poplar in Italy, five 2-year rotations are considered for a 10-year plantation lifetime at a plant spacing of 10 000 plants per hectare generating 14 t ha^{-1} y^{-1}. Production costs at the plant gate amount to 5.5 € GJ^{-1} [39–41], including the opportunity cost of land 0.26 € GJ^{-1} and the cost for local transport 0.5 € GJ^{-1}.

Swedish SRC willow plantation operates seven 3-year rotations at a plant density of 12 000 cuttings per hectare which generates an average of 10 t ha^{-1} y^{-1}. Delivered production costs amount to 4.2 € GJ^{-1} which includes considerable costs for local transport at 1.0 € GJ^{-1} and the opportunity cost of land at 0.26 € GJ^{-1}. A typical Brazilian eucalyptus plantation in the state of Minas Gerais operates three 6-year rotations at a plant density of 1600 plants per hectare and generates a gross yield of 820 m^3 over the 18-year plantation lifetime, equivalent to 18 t ha^{-1} y^{-1}. Production costs for such a configuration amount to 2.8 € GJ^{-1} [42], including 0.5 € GJ^{-1} for local transport costs and 0.1 € GJ^{-1}

Table 3
Summary of improvement options per step of the production cycle specifying concrete activities and indicating the impact on cost reductions illustrated for three crops willow (W), poplar (P) and eucalyptus (E). Some options are relavant to establishing cost reductions but cannot be quantified, for these the table presents a qualitative discussion only.

Step of the production cycle	Activity	Impact on costs	
Yields	Yields can be augmented by: implementing improved varieties, raising inputs, increasing input-use efficiencies, optimizing production, etc.	High: Higher yields are the single most important factor to reduce production costs. The extent depends on actual yield increases.	N.a.
Seedlings and clones			
Breeding and genetic improvements	Improve crop traits: freeze and draught resistance [86–88,90,101].	Potentially high: (shift of production frontier) but uncertain both in timing and impact.	Yield increases < 143% (W)
Seedling selection	Prices for seedlings differ depending on species, genetic quality, etc. Selection of the seedling based on cost considerations may result in lower yields thus reducing revenues over the plantation lifetime [102].	Seedling costs may be related to quality	± 39% (E)
Training	Training can improve seedling quality, prevent plant failure during planting and nursing [91].	Low to mediate	N.a.
Setup and maintenance			
Pest and weed control	Change from manual to chemical weedingReduce frequency of treatments or quantities applied, e.g., by targeting local infestations instead of preventive action.	Low to mediate	−31% (P) −33% (E)
(Reduced) tillage	Limited ploughing operations—only the planting line instead of the entire field [92].	Low to mediate: May reduce organic matter losses and maintain soil fertility [93].	−19% (P)
Fertilization	Timing of fertilization along the production cycle; type of fertilizer used; the amounts supplied to the soil; fertilizer application	Low to high.	−47% (P)
Precision farming	Precision irrigation and nutrient application by implementing tubing close to the rooting system.	Not included in calculations.	N.a.
Rotation management and scale			
Scale of production	Purchase of larger volumes may reduce unit prices, e.g., for fertilizers.	Medium	N.a.
Rotation optimization	– Shorten rotation periods to raise average Yields – Agro-forestry systems: generating additional (net) revenues from intercropping food crops such as beans [95] soy and maize.	Not included in calculation: but potentially high impact	−34 to −65% (E)
Harvest			
Harvesting equipment	(Iterative) optimization of harvesting equipment, e.g., from conventional harvesters for common applications to purpose build harvesters to commercialization of	Low to high	−75% (W)
Outsourcing	Outsourcing of activities to specialized companies that are outside the expertise of farmers, especially harvesting and transport	Can reduce cost through gaining experience faster and by using capital intensive machinery more efficiently.	
Transport	Increase utilization rates, Scale-up operations, reduce overhead. Air-dry harvested stems to reduce moisture content and weight to reduce fuel costs, wearing and toll [94].	Low to mediate	

opportunity cost for land. Further cropping systems specification are described below.

3.3.1. Brazilian eucalyptus

For eucalyptus, land prices have increased slightly in recent years and show large regional variation. While in most states land prices averaged 800–2400 € ha^{-1}, the state of São Paulo experienced prices of up to 4000 € ha^{-1} [43]. Prices for seedlings and cuttings can differ distinctly depending on the species, genetic quality, size of order, distance to market, production efficiency of the nursery, condition of the seedlings, etc. The majority (70–80%) of fertilizer is applied at the plantation setup [44]. Prior to planting, calcium and magnesium is applied to improve the soil structure, neutralise soil acidity and stimulate microbial development. Next, the nutrients phosphorus, nitrogen, potassium and boron are applied in holes around the plant. Finally, the same nutrients are applied to the soil cover. Pest control is the single highest contributor to the costs of setup and maintenance and involves operations to combat insects, mainly ants and termites. Costs are about equally distributed among the costs for pesticide inputs and their application to the field. Other maintenance costs include construction of fire lanes, technical assistance and taxes and fees. Harvesting costs are related to the mechanization level of harvesting operations which in turn is related to the plantation size. Transportation costs for local transport for example from the field to a sawmill depend on transportation distances, vehicle type, road conditions and loading times.

3.3.2. Italian poplar

Historic poplar production in Italy was mainly aimed at fibre production. Because fibre production requires higher quality standards than applications for energy quoted production costs should be considered high. At least higher than what would result from production aimed at energy applications. In particular this applies to costs for establishment, seedlings and maintenance. The purchase costs of land in Italy varies considerably, due to regional variability in land scarcity, but mainly because of variation in the opportunity cost of land [45] depending on the competing land use, e.g., suitable agricultural land versus set-aside land. In southern European settings, Gasol et al. [46] estimate opportunity costs of 0.15–0.50 € GJ^{-1}. Establishment includes tillage, land refining, fertilization and weed control [41]. Fertilization during set up involves application of phosphorus and potassium whereas nitrogen fertilizer is applied mainly at regular intervals during growth. Plantation maintenance involves similar operations including tillage (e.g., pruning, harrowing and weeding), pest control, fertilization and irrigation. The timing, frequency and extent of these activities varies according to site, silviculture, plantation scales, level of professionalization [40]. Irrigation is common but levels depend on local water shortages and management [40]. Harvesting of the coppices takes place every 2–3 years [39].

3.3.3. Swedish willow

Production of willow in Sweden for bioenergy use started in the late 1980s. Rosenqvist et al. [47] argue that the land purchase price does not properly reflects the costs of land. Instead, they suggest to use the opportunity costs as a more adequate measure for land costs associated with willow production. They estimate these costs to be approximately 0–0.5 € GJ^{-1} at present and 0–0.4 € GJ^{-1} in the future. Planting of willow is carried out by a large Swedish agricultural contractor (Lantmännen) who coordinates the planting process; acquiring the cuttings and planting them, operating a one-step planting machine. Typical per hectare nitrogen fertilization is advised at 70 ($\pm$10) kg N in the first year, 110 ($\pm$10) kg N in the second year; no application in the third year [48]. Phosphorus and potassium application is rare, although low-cost waste streams containing those nutrients are applied in some cases. Harvesting equipment is used that cuts the stems and chips them directly [49]. After harvest, wood chips are loaded onto 120 m^3 containers at the road side. Moisture content after harvest and at the time of transport is approximately 50% which is the upper limit that district heating plants can handle. In most cases transport is arranged by the same contractor that takes care of harvesting and that negotiates selling prices with buyers, mainly power plant owners.

4. Past and future performance

4.1. Historic developments

Considerable increases of yields in Italian poplar and Brazilian eucalyptus production were observed in the past (see Fig. 3). Typically, yield improvements by a factor of 3–4 were achieved in both systems between 1950 and 2010. Similar yield increases have also been reported for other forestry plantation systems, such as pine plantations in the Southern United States, where yield increases by a facter of 4 are reported between 1940 and 2000 for intensively-managed pine plantations [112,113]. Remarkably, in Sweden, no sizeable yield improvements were observed, although variations in yield levels exist between high- and low-intensity production systems. This is consistent with the only very modest amounts of willow produced in Sweden, which (from an experience curve approach) would allow for relatively low amounts of learning.

Production costs per ton which are strongly affected by yield increases show a similar picture: significant cost reductions for poplar and eucalyptus and modest developments in Sweden. Below, for each case observed cost reductions and yield developments are discussed in more detail. For Italian poplar an experience curve was fitted to the historical data. For Brazil a progress ratio was estimated on limited data and thus comes with considerable uncertainty.

4.1.1. Brazilian eucalyptus

Yield developments, based on linear regression [59–63], suggest an average yield increase between 1955 and 2010, from 3.1 to 17.4 t ha^{-1} y^{-1} (see Fig. 3). Variations in the data stems from plantation size, level of management intensity and the end use application for which production takes place. Similar yield increases are confirmed for the period of 1970–2000 by Sairanen [111]. Several studies estimate average yearly eucalyptus yields around 20 t ha^{-1} y^{-1} [64–67]. Yield increases resulted especially from technological development, species selection with optimal characteristics and genetic improvements made to species [63]. Bottom-up cost data on Brazilian eucalyptus production are scarce, despite the long production history. Nevertheless, a progress ratio is estimated based on this limited data set. Pereira de Rezende [60] estimate average cost developments for eucalyptus production on *cerrado* in the state of Minas Gerais between the 1960s and 2005. Discounted per hectare, production costs show a 66% decrease over that period, from 14.1 to 4.8k € ha^{-1} for a 21-year plantation, excluding the costs of land and local transport. The observed 66% cost decrease over four decades is in line with what was found for annual cropping systems [10–12]. The bottom-up costs for 2007, presented in Table 2 and Fig. 3, correspond to a cost of 4.2k € ha^{-1} for a 21-year plantation [42]. Cost levels for 1965 (year taken for the 1960s), 2005 and 2007 can be coupled to cumulative production in Brazil for those years. Based on annual production estimates (see Fig. 1), cumulative production experienced 4.4 doublings over that period, increasing from 1.4 to 30 EJ (cumulative). An experience curve fitted to these data points results in a progress ratio of

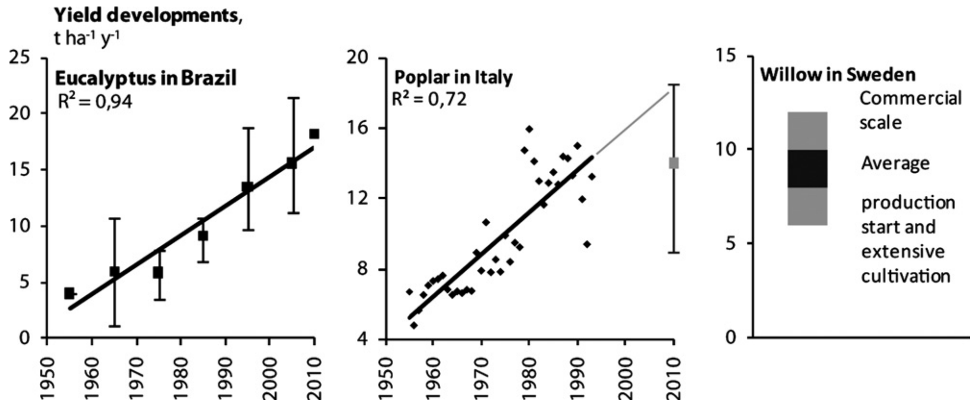

Fig. 3. Yield developments in wood production for poplar, willow and eucalyptus.

63%. Given data limitations, however, the uncertainty is considerable. One particular uncertainty follows from the assumption that the obtained cost reductions result exclusively from experience gained in Brazil. Globally, more than 20.1 million hectares were under eucalyptus production in 2009 to which Brazil contributed one-fifth with more than 4.2 million hectares; followed by India at 3.9, China at 2.6 and Australia at 0.9 million hectares; the remaining (> 42%) eucalyptus production took place in other countries across the globe [68]. When it is assumed that the Brazilian cost level in the 1960s resulted primarily from developments within Brazil, while over time knowledge spill-over from developments in other countries contributed to Brazilian cost decreases, the slope of the experience curve would be flatter than is suggested by the slope (63%) fitted for the isolated Brazilian case. Following this reasoning, the initial 1.4 EJ is kept constant but cumulative production in 2010 is assumed to be approximately five-fold of the 30 EJ calculated for the Brazilian case only which equals to 143 EJ. With unchanged cost levels this leads to a PR of 73%.

The most important cost reduction in Brazil was realized with improved characteristics through breeding. Significant cost reductions were established through mechanization in harvesting as a result of up-scaling and professionalization. Smaller foresters rely on semi-mechanized systems operating chainsaw harvesting which requires extra manpower. Larger forestry companies (paper and pulp, steel, etc.) use highly mechanized methods operating large harvesters that automatically fell, skid, delimb and debark the tree before loading. Transportation costs declined in recent decades due to the outsourcing of transport to specialized companies. As a result vehicle fleets are kept up to date and trucks have increased in size. In addition, these companies cover auxiliary services such as road maintenance, (un)loading, etc. [56]. All these improvements together result in more efficient and cheaper transport services.

4.1.2. Italian poplar

Summation of the yearly production figures shown in Fig. 1 (and extrapolation from 2007 to 2010) indicates an approximate cumulative production of 214 PJ[2] between 1935 and 2010. To estimate yield developments, annual production figures were divided by the yearly area that was felled between 1955 and 1999 [69]. Performing linear regression to the derived yields and applying the obtained parameters to the period 1955–1999 suggests an approximate tripling of average poplar yields from 4.4 to 13.1 t ha^{-1} y^{-1} over those 44 years. For the current situation, the range was given from extensive management (9 t ha^{-1} y^{-1}) to the current average (14 t ha^{-1} y^{-1}) and state-of-the-art levels (18.5 t ha^{-1} y^{-1}) [39]. The data used to quantify past developments in per hectare production costs (at the field level) were based on 14 studies [40,70–82], covering the period 1963–2005 (see Appendix A). Over that period data indicate a 26% cost decrease. For 2010, average production costs were estimated at 4.5 € GJ^{-1} (see the previous section). To these data an experience curve is fitted, indicating a progress ratio of 74 ± 4% with an R^2 of 0.73, reached over nearly four cumulative doublings (see Fig. 4).

The value for 2010 applies to the state-of-the-art rather than to average values. Consequently, this value is low compared to the fitted curve, especially considering that little additional (cumulative) production was established in recent years. However, when the 2010-value is compared to the data points representing the lowest cost-estimates (e.g., 1963, 1981, 1994) they seem in line with these data points. Next, in general terms, the PR falls within the range of PRs found in literature, for example for annual crops used for biofuels [10–12]. The correlation and significance of the fit are reasonable. What introduces uncertainty to the outcomes, however, is the limited number of studies that are available prior to 1980, and a data gap of almost a decade from the mid-1960s to mid-1970s. In addition, the four studies that are available prior to 1980 show large variations between subsequent years (1963 and 1965) and relative to the fitted curve (1976). This variation is among others reflected in the R^2 and the associated uncertainty of 3.5%. However, a change of either of these values could have a considerable impact on the slope of the curve. Uncertainties are discussed in more detail in Section 5.6.

The single most important factor that brought down costs were yield increases. Bergante and Facciotto [39] couple yield levels reached in poplar production directly to the management intensity that is applied, distinguishing between low, medium and high intensity management with the corresponding yield levels 9, 11 and 18.5 t ha^{-1} y^{-1}, respectively. Based on this, average intensity levels in 1955 at 4.4 t ha^{-1} y^{-1} can be considered low while current average yields of 14 t ha^{-1} y^{-1} can be considered medium to high: and thus leave room for future improvement. Since the start of commercial production in the early 1960s, extensive research has been performed to improve yields by developing clonal varieties, by cross-breeding different species and by experimenting with different spacing configurations [83]. With regard to establishment, maintenance and harvesting operations, ongoing mechanization has played a key role in reducing labour inputs. An example is the change from

[2] A linear production increase was assumed from 0 PJ at the start of production in 1935 to 0.56 PJ in 1950, the first year of recording.

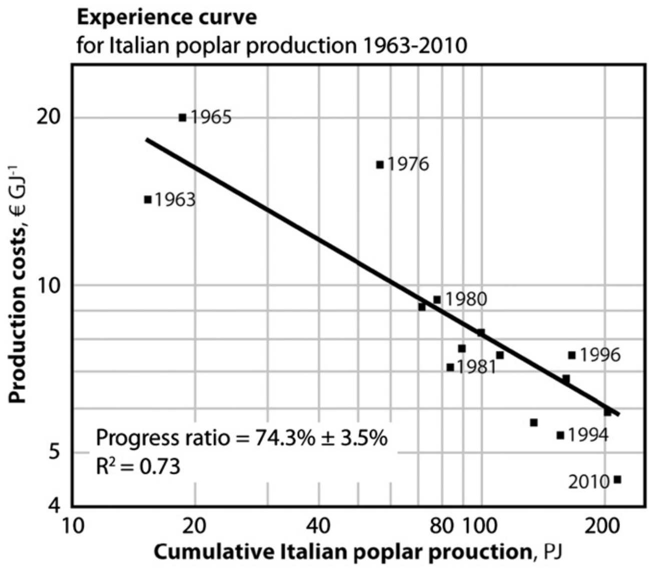

Fig. 4. Experience curve for Italian poplar production for the period 1963–2010. Based on Italian production statistics (ISTAT (Istituto Nazionale di Statistica) [33,69]), areas of poplar felled annually (ISTAT (Istituto Nazionale di Statistica) [33,69]), 14 bottom-up cost studies (Prevosto [71–73,76–78,], Arru and Prevosto [75], Prevosto and Silvestri [74], Frison et al. [79], Borelli et al. [80], Borelli [81], Borelli and Fini [82], Coaloa and Vietto [40]) for the period 1963–2005 and three studies (Coaloa and Vietto [40], Bergante and Facciotto [39], Facciotto [41]) for the state-of-the-costs in 2010. For details see Appendix A. Note: Production costs are stated in 2010 euros.

manual to fully automated tree planting (see Table 3). Another example is the changing harvesting routine: traditional tree harvesting required a laborious harvesting routine of cutting, de-branching and cutting-to-length, for SRC a harvester is used that fells and chips the trees in one pass. While mechanization and experiments on plant varieties have led to major cost decreases, future opportunities are likely to come from optimising input regimes and ground operations (precision farming).

4.1.3. Swedish willow

With 37 PJ of cumulative production to date, willow production in Sweden has achieved only modest scale. Its production is still regarded as an emerging agricultural activity in Sweden [47]. Other countries that have produced willow to some extent include the UK, the US and Poland. The UK had planted 2800 ha by 2008 [84]. Volk et al. [85] provide a comprehensive overview of developments in willow breeding and hybridization which has led to significant yield increases reported by several sources. Breeding programs in Sweden resulted in variable yield increases depending on site-specific circumstances of 12–67% [86,87] and 8–143% in the UK [88]. For example new breeds that are frost-resistant will increase yields more in a region that previously encountered losses due to frost than in a region that had no such problems. Consequently, studies that point out the prospects for cost reductions (see Section 5.1) are more abundant than studies that elaborate on past achievements. Mola-Yudego [89] estimates an increase of average yields in central Sweden between 1990 and 2005 from 6 to 8 t ha^{-1} y^{-1}. Christersson [35] estimates yields of 6–8 t ha^{-1} y^{-1} when extensively managed and 10–12 t ha^{-1} y^{-1} when intensively managed on commercial scale plantations. Key selection criterion for willow is its frost tolerance rather than its yield [49]. Improvements in harvesting operations in recent years have not led cost reductions of harvesting operations because costs for fuel and labor have increased [49].

4.2. Exploring improvement potential and minimum cost levels

Cost reduction options, the preconditions to achieve those and respective uncertainties are summarized in Table 3 and discussed in more detail below. Based on these insights and the cost ranges identified minimum cost levels are derived, shown in Fig. 5.

4.2.1. Brazilian eucalyptus

Delivered costs for Brazilian eucalyptus are projected to ultimately drop from the current 2.8 € GJ^{-1} to just under 2 € at 1.9 € GJ^{-1}. Future cost decreases can be achieved by yield increases through (breakthrough) innovations in breeding and hybridization, further optimization of silvi-culture operations and efficiency improvements in local transport. Efforts in the development of improved traits in species focus on pest and draught resistance [90]. In seedling production and plantation setup, costs can be reduced through training of personnel to improve quality, prevent failure during planting and better nursing at the start of growth [91]. Furthermore, restrictive tillage could save costs [92] while at the same time reducing organic matter losses and maintaining soil fertility and structure [93]. Distinctive to eucalyptus production are the high cost for pest control, in fact the single highest contributor to establishment and maintenance costs. This involves operations to combat insects, mainly ants and termites. Cost can be reduced through the application of pest-resistant breeds and through targeted pest control of local infestations rather than preventive widespread pesticide application. With regard to harvesting, an expansion in the adoption-rates of fully automated harvesting equipment could reduce costs [57]. Average transport costs can be reduced by better planning, further progress in cutting overhead costs and increasing truck-use efficiencies [94]. Couto et al. [95] assessed the cost performance of eucalyptus monocultures versus systems that applied eucalyptus combined with intercropping beans. They conclude that the intercropping system could improve cost performance (overall revenues over the plantation lifetime) with 34–65% per volume of timber harvested [95].

4.2.2. Italian poplar

For Italian poplar production, costs could ultimately be reduced from 5.5 to 2.2 € GJ^{-1}. An increase of yields from current average yields (14 t ha^{-1} y^{-1}) to state-of-the-art levels (18.5 t ha^{-1} y^{-1}) could reduce costs most. The augmentation of yields could be established by further improvements through breeding and through optimizing, chemical pest treatment, soil management and fertilization. With regard to soil management, costs can be cut through the planting of a vegetative (grass) cover which prevents the need for manual, mechanical or chemical weeding. In dry areas the latter measure is not feasible because competition for water is too high. A reduction in fertilization costs and environmental impacts can be achieved by avoiding over-fertilization; through a lower frequency of fertilization along a rotation or by adjusting application rates to actual plant needs (balanced fertilization) [40].

4.2.3. Swedish willow

Current average willow production costs in Sweden amount to 4.4 € GJ^{-1} (see Fig. 2). Further developments in raising yields, improved maintenance and technological improvements of harvesting equipment could reduce costs to 1.9 € GJ^{-1}. These figures are at large in line with values reported in literature: For willow, estimates for delivered costs vary from 4.1 € GJ^{-1} in 2005 [47] to a range specified for willow produced in Northern Europe at 3.5–5.3 € GJ^{-1} [96] and a low estimate at 2.1 € GJ^{-1} (3.0 $ GJ^{-1})

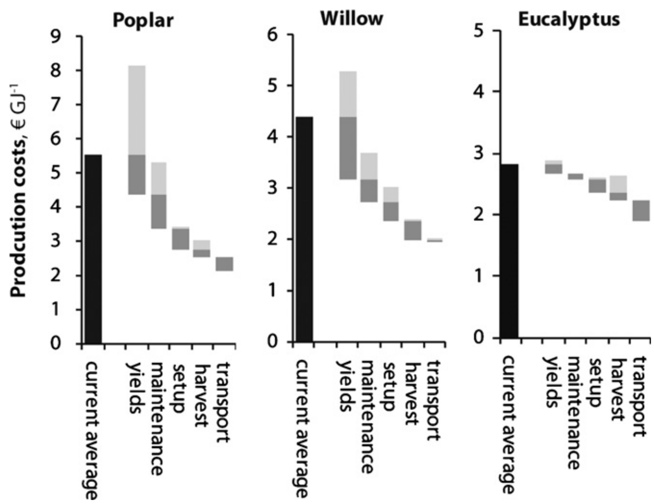

Fig. 5. Derived minimum cost levels, specifying the improvement potential per step of the production cycle.

Table 4
Summary of the production costs, cumulative produced quantities until 2010 and the progress ratios for poplar and eucalyptus.

	Production costs 2010 (€ GJ^{-1})	**Minimum cost levels** (€ GJ^{-1})	**Cumulative production until 2010** (EJ)	**PRs** (%)
European SRC production			0.251	
Willow	4.4	1.9	0.037	–
Poplar	5.5	2.2	0.214	70.8–77.8
Eucalypt in Brazil				
National case	2.8	1.9	30 (Brazil)	62.6 (national)
Global case	2.8	1.9	143 (World)	73.4 (global)

NB—Numbers are rounded in the table. Calculations were based on the actual figures.

for the North-western United States [85]. Cost levels in Poland are slightly lower than in Sweden mainly due to lower labour costs [97]. Additional reduction in establishment costs can be reached through adapted fertilization, e.g., by applying balanced fertilization and by using low-cost fertilization options for example organic waste such as animal manure, sewage sludge and waste water instead of mineral fertilizer [98]. In the first phases of SRC-willow production, harvesting was done by deploying purpose build cutting-heads on conventional harvesters. Problems that occurred were that material was not robust enough leading to fracture and that the flow through harvester and chipper was not optimal which increased harvesting time. Steady optimization has resolved this and further improvements are expected [99]. When improved harvesting equipment is commercially produced in series it is expected that this equipment can be produced at one-fourth of the current costs [49,58]. However, technical and operational improvements made in recent years did not lead to cost decreases due to increased costs for fuel and labor [49]. Transport operations are not expected to have much room for improvement [100]

Fig. 5 shows to what extent production costs can be reduced per step in the production cycle and how this affects the minimum cost levels that can ultimately be achieved. Minimum cost levels imply that all improvement options are realized and assuming productive soils are available. Furthermore, it is assumed that the mechanism that causes cost reductions in one production step does not restrict the potential to reduce costs in another production step. This may lead to slight over-estimation of the calculated minimum cost levels.

4.3. Application of experience curves to biomass demand projections

In the previous sections, bottom-up cost breakdowns, minimum cost levels for the three crops and top-down progress ratios for eucalyptus and poplar were derived. These cost reductions combined with the established cumulative production of wood can be used to derive progress ratios. An experience curve approach can be applied to analyze historic cost developments, assuming that the performance of a cropping system (i.e., production costs) changes by a fixed fraction with every doubling of established production or exercised activity (cumulative volumes of wood produced) [13]. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The progress ratios found for eucalyptus and poplar fall within the broad range (55–80%) that was found for annual crops (see Table 4). The extent to and rate at which cost reductions can occur within the next 20 years, up to 2030, are evaluated in the next section by combining progress ratios with biomass demand projections.

Demand projections such as for primary biomass use worldwide and in Europe suggest that biomass will play a larger role in renewable energy supply. Initially, a large share of the extra demand can be covered by organic wastes, agricultural residues and forest biomass but gradually dedicated production should increase to keep up with demand. Combining the found ranges in progress ratios to demand projections is a top-down exercise that can illustrate to what extent and at what rates large up-scaling of a global or European SRC industry would reduce costs.

Europe's environmental and biofuel policies [103] have accelerated bioenergy production, which is met by a combination of biomass and biofuel imports and domestic production. Between 2005 and 2010, Europe's total primary energy production from biomass increased by 53%, from 3.0 to 4.6 EJ y^{-1}. This value is expected to grow to 6.2 EJ y^{-1} by 2020 according to the national renewable action plans (NREAPs) [104,105]. Furthermore, De Wit et al. [106] assessed techno-economical biomass potentials for Europe until 2030 taking sustainability criteria into account. A maximum of 11.0 EJ of perennial woody crops could be produced by 2030, produced on 66 million hectares of cropland (assumed to become gradually available through agricultural intensification). In an optimistic scenario, it is assumed that production will follow an exponential function to increase from current production volumes to 11 EJ in 2030 to account for a gradual increasing production as is described for early phases of the S-shaped diffusion curve. In reality, it is more likely that a crop mix of sugar, starch, oil and herbaceous grassy crops will be produced. In such a more moderate scenario, perennial SRC crop production is assumed to only reach 2.2 EJ in 2030 (one-fifth of the optimistic scenario).

In 2008, global primary biomass production was 50 EJ of which 12.4 EJ consisted of modern biomass, largely residues, wastes, forest biomass and agricultural crops for biofuels. The IPCC projects values for the primary biomass energy supply to increase from those 50 EJ to 80 (75–85) EJ in 2030 and 138 (120–155) EJ in 2050. In addition to these median figures, upper estimates of 150 EJ in 2030 and 300 EJ in 2050 are given for global biomass demand [2]. To estimate the upper limit of the production that could come from SRC production by 2030, we assume that roughly one-fourth[3] of that 150 EJ consists of SRC, about 38 EJ.

[3] To derive an estimate for the SRC production as a share of global primary biomass production by 2030 a study by Dornburg et al. [107] is used. They define four main categories of biomass feedstocks and attach numbers to their technical potential in 2050. Organic wastes, forestry and agricultural residues represent

Table 5
Application of progress ratios to demand growth projections for energy crops globally and in Europe and its effect on future production costs.

	Cumulative production until 2010 (EJ)	Projected demand by 2030[a] (EJ)	Cumulative demand projection until 2030[b] (EJ)	Doublings in production until 2030[c] (#)	Timing of minimum cost levels reached[d] (Years)
European case					
High case	0.251	11.0	34	7.1	–
Poplar	–	–	–	–	2022–2024
Willow	–	–	–	–	2022–2024
Low case	0.251	2.2	8.5	5.1	
Poplar	–	–	–	–	2025–2027
Willow	–	–	–	–	2024–2026
Global case					
High case	143	38	788	1.9	2021–2025
Low case	30	20	509	1.4	2024–2030

[a] The projected biomass demand quantities by 2030 are discussed in the text.
[b] The cumulative demand projection until 2030 uses cumulative 2010 production levels and assumes an exponential increase to 2030 for the European cases (as developments are in the early stages of the S-shaped diffusion curve), whereas a linear increase is assumed for the global cases (as their development is presumed to be in the linear middle-part of the diffusion curve).
[c] The number of times the cumulative production volume double between 2010 and 2030.
[d] The timing of the moment when the minimum cost levels are reached are based on the initial cost levels in 2010. The progress ratios (either the lower or higher estimate) and the number of doublings reached.

Using the median IPCC value for primary biomass production by 2030 of 80 EJ and applying the one-fourth share of dedicated cropping systems results in 20 EJ.

The analysis suggests that at the assumed growth rates for biomass, minimum cost levels could be reached between one and two decades. For eucalyptus production, considering its already substantial production thus far, absolute cost reductions are reached at a slower pace. Assuming global deployment of eucalyptus based SRC, minimum cost levels could be reached between 2021 and 2025. If production (and thus learning) is restricted to Brazil, minimum cost levels are reached between 2024 and 2030 (Table 5).

However, given the modest European production so far, rapid doublings of cumulative production could be achieved, which would allow in principle for rapid learning and cost reductions. Assuming a gradual (but ultimately significant) transition to the large-scale production of willow and poplar (with would require dedicated policy support), minimum cost levels could in theory be reached between 2022 and 2027, roughly equalling the Brazilian production costs. Such a scenario is not impossible, but should be treated with caution: the policy measures to achieve such growth would need to be substantial and require significant up-front learning investment, which is unlikely to happen. Also, SRC systems are perennial, so typically 2–5 years are needed to pass on gained experience and apply it to a next generation. Nevertheless, similar cost reduction *have* already been achieved in the past, e.g., for traditional eucalyptus production in Brazil or corn production in the US. To achieve such cost reductions, simultaneous dedicated private and public R&D efforts would probably be needed, similar to for example the past Brazilian development of eucalyptus (and sugarcane for that matter). In addition, it can be argued that, given the similarities of (the improvement potentials of) steps in the production cycle (see Table 3), global SRC systems may over time develop into a single global learning system which, from the insights gained in this analysis, causes more rapid learning and consequent cost reductions.

(*footnote continued*)
~110 EJ. Biomass produced by perennial cropping systems on better lands adds ~120 EJ y^{-1}. Production on degraded and marginal lands could add another ~70 EJ. Surplus forest growth represents ~100 EJ y^{-1}. These numbers provide an indication on how IPCC projections are broken down by 2050. The summed total amounts ~500 EJ y^{-1} thus perennial cropping systems contribute roughly one-fourth.

5. Conclusions and discussion

The present paper gives an overview of past developments, the current status and an outlook of costs and yield developments in dedicated wood production systems for energy use for poplar, willow and eucalyptus. A main objective was to evaluate the extent to which experience curves could be applied to perennial wood production systems. To evaluate the future cost reduction potential for dedicated wood cropping systems, bottom-up insights and top-down approaches (including experience curves) were combined and applied to global and European demand projections to sketch scenarios for future deployment of SRC systems and possible developments in production costs.

Current average production cost levels are highest for poplar (5.5 € GJ^{-1}), followed by willow (4.4 € GJ^{-1}) and eucalyptus (2.8 € GJ^{-1}). Based on the cost reduction options minimum cost levels are derived for all crops around 2 € GJ^{-1}.

Past cost developments indicate that per hectare cultivation costs have decreased by roughly two-thirds in recent decades for poplar in Italy and eucalyptus in Brazil. For Sweden, due to the limited volumes produced, no overall cost decline was observed over the two decades that willow is produced. In all cases significant variations in yield levels are observed that depend on site specific soil and climate conditions and the intensity level of the cultivation. Yield increases have been the most important driving force behind production cost declines. Yields were augmented through implementation of improved breeds and clonal varieties, increased fertilization levels, better pest control and ongoing mechanization in planting and tillage. Further progress, outside the cropping system, was reached in harvesting and local transport. In harvesting, ongoing mechanization and improvements that were made to harvesting equipment were the most important aspects. In transport, improved road networks, increasing truck-size and truck reliability and improving use-efficiencies have brought down costs. An option not quantitatively considered in the present study but with the potential to improve overall plantation revenues considerably is the application of agro-forestry systems [95].

It has proven difficult to derive empirical progress ratios for the assessed cases due to limitations and heterogeneity of data, although the extent and type of these limitations varied per case. Poplar production in Italy presents the best case that was assessed in the present study due to the availability of bottom-up cost overviews for consecutive years. Variation in the cost data with

regard to steps of the production cycle included, rotation periods and plantations lifetimes considered required data adjustments to compare data. For Brazil limited cost data were available. To derive progress ratios the cumulative produced volumes were varied, applying cost levels to Brazilian and global production.

Given data limitations, the derived progress ratios should be considered first order estimates. The resulting progress ratios indicate that considerable cost reductions are possible. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The progress ratios found for eucalyptus and poplar fall within the broad range (55–80%) that was already found for annual crops. On average, it appears that PRs for the production of annual and perennial crops seem to be on the low side, i.e., cost reduction occurs faster compared to other energy supply technologies that display a mean progress ratio of 84% [7]. It should, however, be pointed out that to some extent the learning involved with forest plantations is local, i.e., aimed at optimizing yields for local circumstances. Again this emphasizes the fact that these outcomes should be seen as first order estimates and that actual improvement potentials may vary depending on specific local conditions. Nevertheless, substantial spill-over between regions exists. An example is improved eucalyptus seedlings from Brazil that may well be employed in regions with similar climatic conditions. Furthermore, because exogenous factors such as cost for labour, land, fertilizer and diesel play a major role in the total production costs and depend on market developments they are not subject to learning as such. In addition, the fact that future yield increases may be more difficult to achieve over time could result in lower cost reductions and eventually in reaching minimum cost levels. However, for the next 10–20 years outcomes suggest that, on average, significant reductions are possible.

The fact that future cost projections do not explicitly consider variations in exogenous cost factors, unrelated to technological progress (such as prices for land, labour and inputs), introduces additional uncertainty in the outcomes. Prices paid for diesel and nitrogen fertilizers are influenced by fossil fuel prices. Considerable volatility and current high price levels show the variability of these inputs and their impact on the prices of manufactured goods. The (opportunity) costs of land depend on (local) scarcity. As a result of an increased demand for biomass feedstocks, on top of rising food demand, the demand for agricultural land may rise this can lead to higher land prices [107]. Labour costs, although in general not very volatile, generally rise as economic development continues. To illustrate the labour cost differences: wage levels were about one-tenth in Brazil of what they were in Sweden in 2000 [108]. This usually leads to deployment of more capital reducing the role of labour.

The crucial role of stimulating policies for the establishment and growth of production volumes and subsequent cost reductions has been apparent in all three cases. In Brazil, two national programs have increased eucalyptus production greatly—a reforestation program focussed on securing forest supplies while another aimed at substituting imported fossil fuels by forest products. In Sweden, in the 1980s, research grants led to the development of improved varieties such as frost resistant species which boosted yields. For poplar in Italy, government intervention had been modest. However, a financial aid scheme to financially assist farmers had actually increased production figures until it was abolished because it appeared conflicting with EU policy. Nevertheless, the possible influence of exchange of experience and learning beyond national borders remains unclear and requires more in-depth analysis.

The scenario outcomes suggest that when European biomass ambitions are increasingly met by European SRC production, learning induced cost reductions could be achieved fairly rapidly, and minimum cost levels of around 2 € GJ^{-1} could be reached for poplar and willow on better quality lands between 2022 and 2027. For eucalyptus production, considering its substantial production thus far, absolute cost reductions are reached at a somewhat slower pace. At fast global deployment of eucalyptus-based SRC, minimum cost levels of again 2 € GJ^{-1} could be reached between 2021 and 2025. When learning is restricted to Brazil, minimum cost levels would be reached between 2024 and 2030 but this is a hypothetical case. Note that cost reduction potentials for eucalyptus in Brazil are relatively limited in part because Brazil already produces pulp at the lowest costs globally [112]. Therefore, it can be speculated that cost reduction potentials in other world regions can be higher.

This analysis suggest that in principle, the EU might produce lignocellulose at cost-competitive levels within the next 15–20 years, However, both progress ratios and production projections remain uncertain. Realizing such deployment and cost reduction would also require a EU-wide dedicated policy effort and large up-front learning investments. Nevertheless, the findings warrant further research into experience curves for perennial crops. The paper points out methodological issues regarding the lack of data, difficulties of comparing various crop types and production systems and the importance of geographical system boundaries. Further investigation could focus on the production of (in particular) eucalyptus in other countries than Brazil, advances in other lignocelluloses crops, but also more annual crops to get a better (and more quantitative) overall understanding of future learning potential of various crop types. Next, a component experience curve [109,110] could be applied to evaluate more in-depth which steps in the cropping system have contributed and can contribute to deliver cost reductions in the future. Furthermore, the found progress ratios for SRC systems could be deployed in energy scenario modelling, e.g., to assess the effect of policy interventions on the rate at which cost reduction are reached, also in relation to competing production systems such as between power generation and biofuels.

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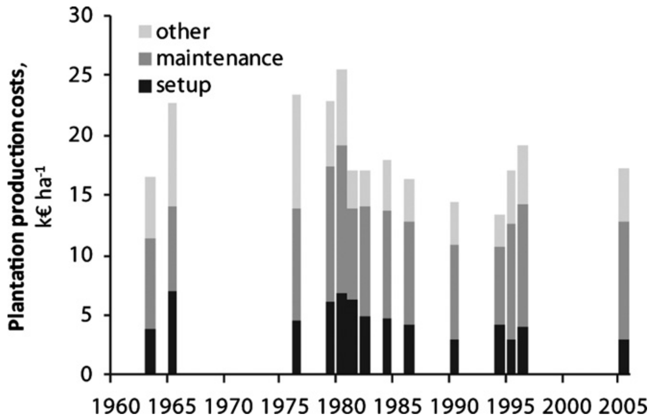

Fig. 6. Breakdown of Italian poplar production costs per hectare for a typical plantation lifetime of 10 years; displayed are 14 bottom-up cost studies [40,70–82], executed between 1963 and 2005 Note: Production costs are presented for 2005 euros.

Appendix

Italian poplar production

The breakdown of poplar production csts per hectare over time presented in (Appendix A—Fig. 6) shows large variation in cost levels. Large cost variations from one year to the next (e.g., 1980–1981 or 1994–1995) suggest differences in methods used, steps of the production cycle included or other differences in the approaches applied. A linear regression trend line was fitted to the 14 data points showing an average reduction of total costs of -26%, from 23.4 to 13.8k € ha^{-1}, between 1963 and 2005. As is clear from the graphic the variation between values is high which is reflected in a poor R^2-score of 0.27. Further scrutiny of the relative contributions to overall cost reductions reveal the largest decline in setup costs (-61%), followed by maintenance (-16%) and other costs (-1%). The initial increase in maintenance costs can be related to increasing use of fertilisers and other inputs in a time when plantations professionalized also reflected in progressively higher yields that were established (see Fig. 5).

Data adjustments

Some adjustments had to be performed to the data to make them better comparable. In the 1994 study [80], no costs for irrigation were considered in contrast to the other studies. As an estimate for irrigation costs in 1994, the average costs were taken from 1990 [79] and 1995 [81]. The study for 1965 [71] considered a plantation lifetime of 15 years compared to the other studies that considered a 10-year lifetime. While this did not affect the cost for the plantation setup, the costs for maintenance and other cost were adjusted for this difference. The 1990 study did not consider fiscal costs and some costs for maintenance; these were taken from the 1986 study. Furthermore this study assumed a 6-year plantation lifetime for which maintenance costs were adjusted to make it comparable to the general 10-year plantation lifetime.

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